OFDM for Wireless Communications Systems

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1.2 Orthogonal Frequency-Division Multiplexing

Over the past few years, there has been increasing emphasis on extending the services available on wired public telecommunications networks to mobile/movable nonwired telecommunications users. At present, in addition to voice services, only low-bit-rate data services are available to mobile users. However, demands for wireless broadband multimedia communication systems (WBMCS) are anticipated within both the public and private sectors. Wired networks are cannot support extension to wireless mobile networks because mobile radio channels are more contaminated than wired data-transmission channels. We also cannot preserve the high QoS required in wired networks [2].

The mobile radio channel is characterized by multipath reception: the signal offered to the receiver contains not only a direct line-of-sight (LOS) radio wave, but also a large number of reflected radio waves that arrive at the receiver at different times. Delayed signals are the result of reflections from terrain features such as trees, hills, mountains, vehicles, or buildings. These reflected, delayed waves interfere with the direct wave and cause intersymbol interference (ISI), which in turn causes significant degradation of network performance. A wireless network should be designed to minimize adverse effects.

To create broadband multimedia mobile communication systems, it is necessary to use high-bit-rate transmission of at least several megabits per second. However, if digital data is transmitted at the rate of several megabits per second, the delay time of the delayed waves is greater than 1 symbol time. Using adaptive equalization techniques at the receiver is one method for equalizing these signals. There are practical difficulties in operating this equalization at several megabits per second with compact, low-cost hardware.

To overcome such a multipath-fading environment with low complexity and to achieve WBMCS, this chapter presents an overview of the orthogonal frequency-division multiplexing (OFDM) transmission scheme. OFDM is one of the applications of a parallel-data-transmission scheme, which reduces the influence of multipath fading and makes complex equalizers unnecessary.

1.2.1 History of OFDM

OFDM is a special case of multicarrier transmission, where a single data stream is transmitted over a number of lower-rate subcarriers (SCs). It is worth mentioning here that OFDM can be seen as either a modulation technique or a multiplexing technique. One of the main reasons to use OFDM is to increase robustness against frequency-selective fading or narrowband interference. In a single-carrier system, a single fade or interferer can cause the entire link to fail, but in a multicarrier system, only a small percentage of the SCs will be affected. Error-correction coding can then be used to correct for the few erroneous SCs. The concept of using parallel-data transmission and frequency-division multiplexing (FDM) was developed in the mid-1960s [28, 29]. Some early development is traced back to the 1950s [30]. A U.S. patent was filed and issued in January 1970 [31].

In a classical parallel-data system, the total signal frequency band is divided into N nonoverlapping frequency subchannels. Each subchannel is modulated with a separate symbol, and then the N subchannels are frequency multiplexed. It seems good to avoid spectral overlap of channels to eliminate interchannel interference. However, this leads to inefficient use of the available spectrum. To cope with the inefficiency, the ideas proposed in the mid-1960s were to use parallel data and FDM with overlapping subchannels, in which each, carrying a signaling rate b, is spaced b apart in frequency to avoid the use of high-speed equalization and to combat impulsive noise and multipath distortion, as well as to use the available bandwidth fully.

Figure 1.10 illustrates the difference between the conventional nonoverlapping multicarrier technique and the overlapping multicarrier modulation technique. By using the overlapping multicarrier modulation technique, we save almost 50% of bandwidth. To realize this technique, however, we need to reduce cross talk between SCs, which means that we want orthogonality between the different modulated carriers.

The word "orthogonal" indicates that there is a precise mathematical relationship between the frequencies of the carriers in the system. In a normal FDM system, many carriers are spaced apart in such a way that the signals can be received using conventional filters and demodulators. In such receivers, guard bands are introduced between the different carriers and in the frequency domain, which results in a lowering of spectrum efficiency.

It is possible, however, to arrange the carriers in an OFDM signal so that the sidebands of the individual carriers overlap and the signals are still received without adjacent carrier interference. To do this the carriers must be mathematically orthogonal. The receiver acts as a bank of demodulators, translating each carrier down to dc, with the resulting signal integrated over a symbol period to recover the raw data. If the other carriers all beat down the frequencies that, in the time domain, have a whole number of cycles in the symbol period T, then the integration process results in zero contribution from all of these other carriers. Thus, the carriers are

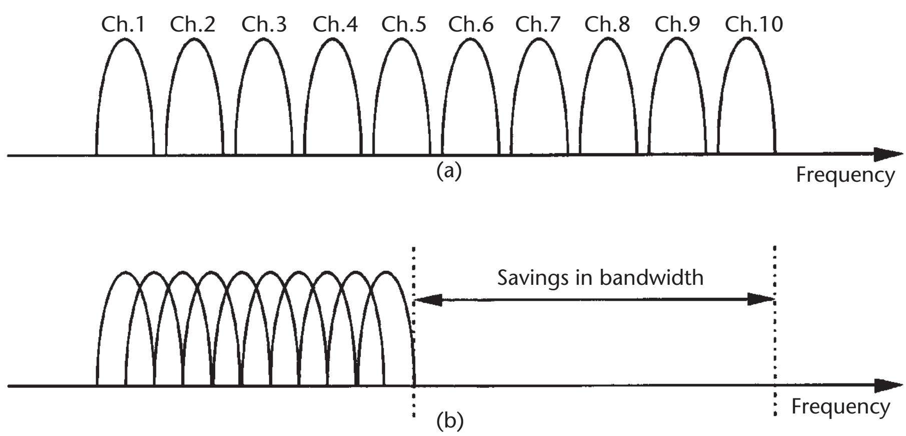

Figure 1.10 Concept of the OFDM signal: (a) conventional multicarrier technique, and (b) orthogonal multicarrier modulation technique.

linearly independent (i.e., orthogonal) if the carrier spacing is a multiple of $1/T$. Chapter 4 presents in detail the basic principle of OFDM.

Much of the research focuses on the highly efficient multicarrier transmission scheme based on "orthogonal frequency" carriers. In 1971, Weinstein and Ebert [32] applied the discrete Fourier transform (DFT) to parallel-data-transmission systems as part of the modulation and demodulation process. Figure 1.11(a) shows the spectrum of the individual data of the subchannel. The OFDM signal, multiplexed in the individual spectra with a frequency spacing b equal to the transmission speed of each SC, is shown in Figure 1.11(b). Figure 1.11 shows that at the center frequency of each SC, there is no cross talk from other channels. Therefore, if we use DFT at the receiver and calculate correlation values with the center of frequency of each SC, we recover the transmitted data with no cross talk. In addition, using the DFT-based multicarrier technique, FDM is achieved not by bandpass filtering but by baseband processing.

Moreover, to eliminate the banks of SC oscillators and coherent demodulators required by FDM, completely digital implementations could be built around special-purpose hardware performing the fast Fourier transform (FFT), which is an efficient implementation of the DFT. Recent advances in very-large-scale integration (VLSI) technology make high-speed, large-size FFT chips commercially affordable. Using this method, both transmitter and receiver are implemented using efficient FFT techniques that reduce the number of operations from N^2 in DFT to $N\log N$ [33].

In the 1960s, the OFDM technique was used in several high-frequency military systems such as KINEPLEX [30], ANDEFT [34], and KATHRYN [35]. For example, the variable-rate data modem in KATHRYN was built for the high-frequency band. It used up to 34 parallel low-rate phase-modulated channels with a spacing of 82 Hz.

In the 1980s, OFDM was studied for high-speed modems, digital mobile communications, and high-density recording. One of the systems realized the OFDM techniques for multiplexed quadrature amplitude modulation (QAM) using DFT [36]; also, by using pilot tone, stabilizing carrier and clock frequency control and trellis coding could also be implemented [37]. Moreover, various-speed modems were developed for telephone networks [38].

In the 1990s, OFDM was exploited for wideband data communications over mobile radio FM channels, high-bit-rate digital subscriber lines (HDSL; 1.6 Mbps),

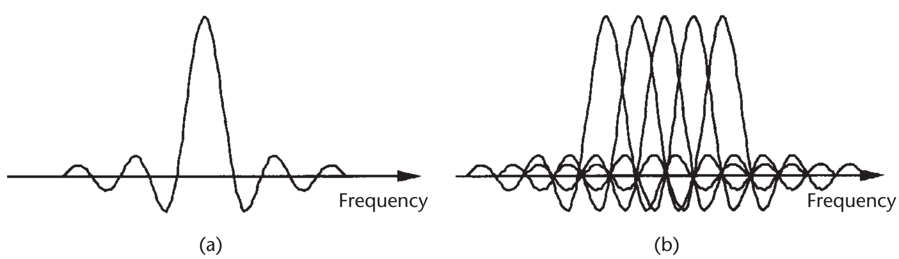

Figure 1.11 Spectra of (a) an OFDM subchannel, and (b) an OFDM signal.

asymmetric digital subscriber lines (ADSL; up to 6 Mbps), very-high-speed digital subscriber lines (VDSL; 100 Mbps), digital audio broadcasting (DAB), and high-definition television (HDTV) terrestrial broadcasting [39–46].

The OFDM transmission scheme has the following key advantages:

- OFDM is an efficient way to deal with multipath; for a given delay spread, the implementation complexity is significantly lower than that of a single-carrier system with an equalizer.
- In relatively slow time-varying channels, it is possible to enhance capacity significantly by adapting the data rate per SC according to the signal-to-noise ratio (SNR) of that particular SC.
- OFDM is robust against narrowband interference because such interference affects only a small percentage of the SCs.
- OFDM makes single-frequency networks possible, which is especially attractive for broadcasting applications.

On the other hand, OFDM also has some drawbacks compared with single-carrier modulation:

- OFDM is more sensitive to frequency offset and phase noise.
- OFDM has a relatively large peak-to-average-power ratio, which tends to reduce the power efficiency of the radio frequency (RF) amplifier.

1.3 Concluding Remarks

Multicarrier techniques, including OFDM-based wireless systems, will provide the solution for future-generation wireless communications. The following provides some of the justification:

1. Multicarrier techniques can combat hostile frequency-selective fading encountered in mobile communications. The robustness against frequency-selective fading is very attractive, especially for high-speed data transmission.
2. OFDM scheme has matured well through research and development for high-rate WLANs and terrestrial DVB. We have developed a lot of know-how for OFDM.
3. Combining OFDM with CDMA yields synergistic effects, such as enhanced robustness against frequency-selective fading and high scalability in possible data-transmission rates.

Figure 1.12 shows the advantages of multicarrier techniques.

The real challenge for the future can be explained by (1.1) to achieve IP-based wireless multimedia communications:

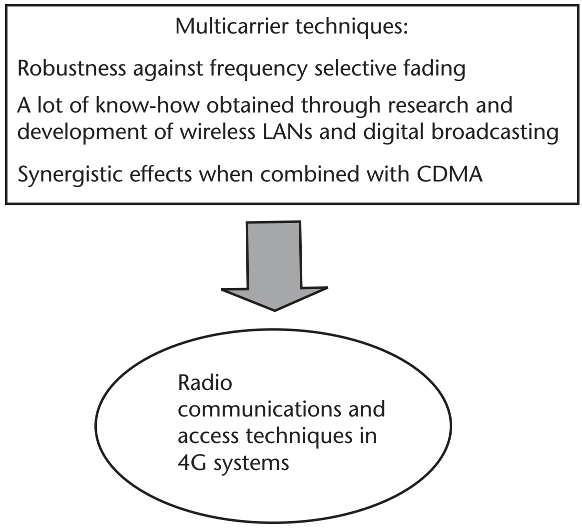

Figure 1.12 Advantages of multicarrier techniques for 4G systems.

$$E \propto m.c^4 \tag{1.1}$$

where E is evolution of wireless communications, m is multimedia communications, and c is consumer electronics, computer technology, communications technology, and contents. Figure 1.13 illustrates the clue to the evolution/revolution of wireless IP-based multimedia communications.

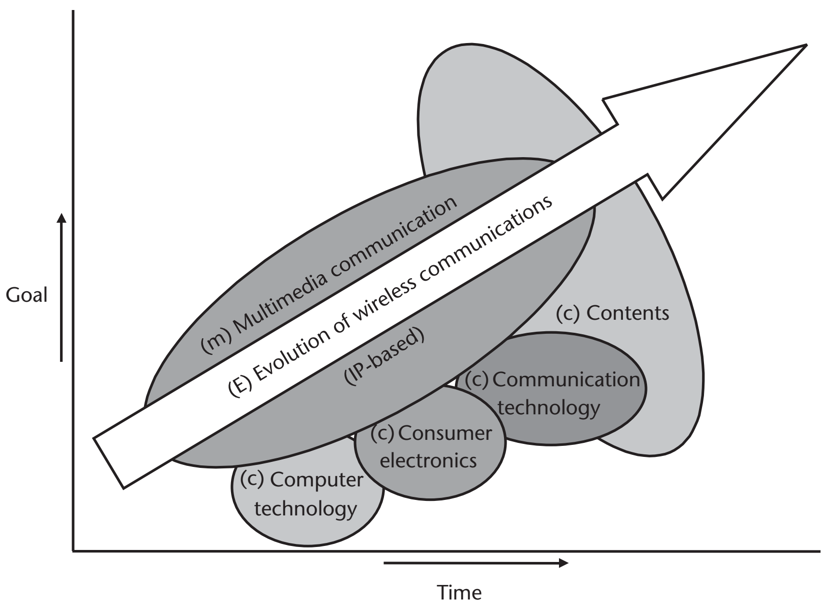

Figure 1.13 Evolution/revolution of wireless IP-based multimedia communications.